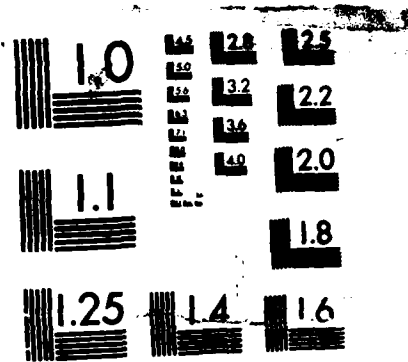


AD-A181 301 BOUNDARY LAYER SEPARATION IN 2 AND 3 DIMENSIONAL HIGH 1/1  
SPEED BLOW(D) CALIFORNIA UNIV BERKELEY COLL OF  
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5. MONITORING ORGANIZATION REPORT NUMBER(S)

AFOSR-TR- 87-0696

6a. NAME OF PERFORMING ORGANIZATION  
UNIV CA, BERKLEY6b. OFFICE SYMBOL  
(If applicable)7a. NAME OF MONITORING ORGANIZATION  
AFOSR/NA6c. ADDRESS (City, State and ZIP Code)  
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BERKELY, CA 947207b. ADDRESS (City, State and ZIP Code)  
BUILDING 410  
BOLLING AFB, DC 20332-64488a. NAME OF FUNDING/SPONSORING  
ORGANIZATION  
AFOSR/NA8b. OFFICE SYMBOL  
(If applicable)9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER  
AFOSR-83-01998c. ADDRESS (City, State and ZIP Code)  
BUILDING 410  
BOLLING AFB, DC 20332-6448

10. SOURCE OF FUNDING NOS.

PROGRAM  
ELEMENT NO  
61102FPROJECT  
NO.  
2307TASK  
NO.  
A1WORK UNIT  
NO.

11. TITLE (Include Security Classification)

(U) BOUNDARY LAYER SEPARATION IN 2 AND 3 DIMENSIONAL HIGH SPEED FLOW

12. PERSONAL AUTHOR(S)

M HOLT

13a. TYPE OF REPORT  
FINAL13b. TIME COVERED  
FROM TO14. DATE OF REPORT (Yr., Mo., Day)  
MAY 198715. PAGE COUNT  
10

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD GROUP SUB GR

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

BOUNDARY LAYERS, LMINAR FLOW, SUPERSONIC FLOW

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Laminar boundary flow on cones in supersonic flow was calculated using a modified Method of Integrals to account for the change in velocity profiles in the separated regions. The work was extended to three dimensions and compared to experimental data. Significant progress was made in the modeling of the flows and in particular the regions of separated and reverse flow in the boundary layer.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT

UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION

UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL

HENRY E HELIN, CAPTAIN, USAF

22b. TELEPHONE NUMBER  
(Include Area Code)

202-767-4935

22c. OFFICE SYMBOL

AFOSR/NA

**AFOSR-TR- 87-0696**

**BOUNDARY LAYER SEPARATION IN TWO AND THREE DIMENSIONAL  
HIGH SPEED FLOW**

**FINAL REPORT FOR AFOSR 83-0199**

**by**

**MAURICE HOLT**

**MAY 1987**

**AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)  
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Grant AFOSR 83-0199  
Final Scientific Report

Summary of Work May 1983 - April 1984

During this period the main research effort was directed to the calculation of laminar boundary flow on circular cones in supersonic flow at high angles of attack. This problem has been examined previously by Fletcher and Holt (1976) and by Holt and Chan (1979). However, the earlier calculations were confined to the boundary layer regions upstream of the cross-flow separation line and emphasis was now made on continuation of boundary layer calculations in regions of reversed flow downstream of the separation line, on the leeward side of the cone. The method used for these calculations was based on the same formulation of the Method of Integral Relations as that used by Fletcher and Holt, but modified to take account of the change in velocity profiles in separated regions.

During this period the Principal Investigator spent a great deal of time on preparation of an invited survey paper presented at the Computational Techniques and Applications Conference in Sydney, New South Wales, Australia in August 1983. This surveyed the general development of Numerical Methods in Fluid Dynamics over the past four decades. The part of the survey relevant to the grant dealt with Boundary Layer Problems.

In the same period the Principal Investigator also worked on the revised second edition of his book, Holt (1984). This included an expansion of the chapter on the Method of Integral Relations especially its application to turbulent boundary layers and to internal three dimensional boundary layer flows.

## References

Fletcher, C.A.J. and Holt, M., J. Fluid Mech. 74 561-591, 1976.

Holt, M. and Chan, W.K., Lecture Notes in Physics 91, Springer-Verlag, 1979.

### Summary of Work May 1984 - April 1985

During this period the calculations of viscous flow past sharp nosed cones in supersonic flow at high angles of attack were continued. The approach was based on an inviscid-viscous interaction model developed by Fletcher and Holt (1976) and Holt and Chan (1979). The approach was extended by Holt and Aghazadeh (1985) to deal with the revised boundary layer flow beyond the cross flow separation line towards the leeward side of the cone. The problem provides an example of three dimensional separated flow which can be treated by the Method of Integral Relations. The algebraic formulation was completed in 1984 and is based on expansions in polynomials, avoiding the use of square root singularities which arise in two dimensional separation. The formulation took some time to program since it consisted of a number of subsidiary routines which had to be matched together. The inviscid flow itself was treated by three different techniques. On the windward side of the cone, between the cross flow stagnation and sonic lines the Method of Lines was used. In the mid cross flow region, where the cross flow is supersonic, the Method of Characteristics was used. On the leeward side of the cone an internal shock wave develops which must be fitted so that the zero cross flow velocity conditions are satisfied on the leeward plane of symmetry. The boundary layer flow was also handled differently in the three cross flow regions. On the windward side, the viscous flow is strongly coupled with the subsonic inviscid flow and an iterative proce-

ture is required (similar to that used in Wigton and Holt (1981)) to ensure that the cross flow displacement thickness is compatible with the surface pressure distributions at the edge of the boundary layer. The mid cross flow region is easier to treat since local slope of displacement is directly proportional to the outside pressure distribution so that no iteration is needed. Separation occurs within the latter region and it is in the reversed cross flow region beyond separation where the modified form of the Method of Integral Relations was developed. As the windward region is approached the cross flow reattaches and the pressure approaches an essentially constant value (as predicted in Holt (1952)). The treatment here was similar to that in other constant pressure problems (see, for example, Yang and Holt (1984)).

Mention should be made of experimental work on another problem concerning three dimensional boundary layer separation in supersonic flow, namely, supersonic flow past a circular cylinder mounted normal to a flat plate. This was carried out in the 13 cm x 13 cm Supersonic Wind Tunnel at the University of California, Berkeley and was the subject of the Ph.D. thesis by Oktay Ozcan. The work was partially supported by the Grant and is published in Ozcan and Holt (1984). The flow patterns revealed in this experiment are complex and very interesting, introducing multiple separations and reattachments of a three dimensional character. Strangely enough, the flow pattern becomes simpler as the free stream Reynolds number changes from the laminar to the turbulent range. The flow field is of basic interest since it models body-surface interference and merits further study. As far as is known, the problem has not been treated numerically up to this point.

The Principal Investigator presented two papers (one invited) related to work under the Grant, the first a short course preceding the BAIL III Conference at Trinity College, Dublin, the second at the Ninth International Conference on Numerical Methods in Fluid Dynamics.

#### References

- Fletcher, C.A.J. and Holt, M., J. Fluid Mech 74 561-591, 1976.  
Holt, M. and Chan, W.K., Lecture Notes in Physics 91, Springer-Verlag, 1979.  
Holt, M. and Yang, R.-J., J. Appl. Mech. 51 27-34, 1984.  
Holt, M. and Quart, J. of Mech. and Applied Math. VII 438-445, 1954.

#### Summary of Work May 1985 - October 1986

During this period a number of contributions were completed on problems related to boundary layer separation.

Firstly a paper was presented at the 10th ICNMF meeting in Beijing. This treated boundary layer flow beyond separation using equations in the Dorodnitsyn integral form but solved by a finite element method rather than by the method of integral relations. This means that the streamwise velocity component is still used as the independent variable in the downstream direction. However the local shearing stress across the boundary layer is represented by a series of linear (or quadratic) finite elements rather than by a single algebraic expansion spanning the whole boundary layer thickness. This change simplifies the handling of reversed flow profiles and has been shown to be successful in application to a flow field simulating a supersonic compression corner. Christopher Pace, a recent graduate student, assisted in this work.



Secondly the Principal Investigator presented a keynote address at the BAIL IV Conference in July 1986, in Novosibirsk, USSR (organized by John Miller and S.K. Godunov). This is a review of the treatment of boundary layer flow including separation by a viscous-inviscid interaction approach. This has been very successful for calculations of two dimensional flow, including airfoil flow, but runs into difficulties, especially in regions downstream of separation, in the complex three dimensional flow fields encountered at the present time.

The third publication is based on the Ph.D. thesis of Jeffrey D. Brown, a recent Mechanical Engineering graduate student, completed in the spring semester 1986. This concerns an experimental investigation of turbulent boundary layer flow past a sphere-cylinder model with a conical flare afterbody. Three-dimensionality is introduced into the flow by setting the flare in unsymmetrical attitudes with respect to the sphere cylinder forebody. Observations are concentrated on the upper plane of symmetry of the body and are based on two component LDV traverses and static pressure measurements. The experiments were carried out at AMES Research Center under the supervision of Joe Marvin with the principal investigator as faculty thesis chairman. The work was presented as a joint paper (J.D. Brown, J.L. Brown, M.I. Kussoy, C.C. Horstmann and M. Holt) at the 25th AIAA Aerospace Sciences Meeting in January 1987. A further paper is planned, for a forthcoming AIAA meeting, in which the flow fields discussed in Jeff Brown's thesis will be calculated by the numerical methods developed under the grant, providing material for a comparative study. This will be prepared by the principal investigator and a research assistant.

The fourth publication based on a Ph.D. thesis by Ehsan Ettehadieh, a recent graduate student supervised by the principal investigator, concerns a study of the effect of normal injection on turbulent boundary layer flow and is an example of successful application of the Orthogonal Method of Integral Relations to turbulent boundary layer calculations.

The fifth publication concerns an experimental investigation of turbulent flow in a curved pipe and provides relevant data on secondary turbulent flow fields. This originated in another Ph.D. thesis (by Yannis Kliafas) supervised by the principal investigator.

Finally, Virginie Daru, Maitre Assistant at ENSAM, Paris, spent 3 months at U.C. Berkeley as a Visiting Professor with support from the grant and completed a paper concerned with more efficient implicit finite difference schemes for solving the Euler equations.

### Papers Presented

1983 International Conference on Computational Techniques and Applications. University of Sydney, Australia, August 1983. "The Changing Scene in Computational Fluid Dynamics"

BAIL III Conference. Advances in Computational Methods for Boundary and Interior Layers. International Short Course, 18-19 June 1984, Trinity College, Dublin, Ireland. "Numerical Techniques for Treating Boundary Layer Separation in Two and Three Dimensions"

10th International Conference on Numerical Methods in Fluid Dynamics, Beijing, People's Republic of China, June 1986. "Calculation of Flow in a Supersonic Compression Corner by the Dorodnitsyn Finite Element Method"

Keynote Address, BAIL IV Conference, Novosibirsk, USSR, July 1986. "Treatment of Boundary Layer Separation Using Viscous-Inviscid Interaction Models"

Publications (supported wholly or in part by grant)

Sydney lecture published in Computational Techniques and Applications, CTAC 83, J. Noye and C. Fletcher, Editors, pp 15-30, North Holland, 1984.

M. Holt and W-S. Yeung, "A Numerical Investigation for Curved Pipe Flow of High Reynolds Number", J. Applied Mechanics 50, pp 239-250, 1983.

M. Holt (with E.C. Baroth), "Investigations of Supersonic Separated Flow in a Compression Corner by Laser-Doppler Anemometry Experiments", Experiments in Fluids 1, pp 195-203, Springer-Verlag, 1983.

M. Holt, Numerical Methods in Fluid Dynamics, Springer Series in Computational Physics, Second Edition, Springer-Verlag, 1984.

BAIL III lecture published in Advances in Computational Methods for Boundary and Interior Layers (ed. J.J.H. Miller), Boole Press, Dublin, Ireland, 1984.

M. Holt (with R.J. Yang), "Boundary Layer Control by Means of Strong Injection," J. Applied Mechanics 51, pp 27-34, 1984.

M. Holt (with O. Ozcan), "Supersonic Separated Flow Past a Cylindrical Obstacle on a Flat Plate," AIAA Journal 22, pp 611-617, 1984.

M. Holt (with M. Aghazadeh), "Supersonic Flow Past Circular Cones at High Angles of Yaw, Downstream of Separation," Proceedings of the Ninth International Conference on Numerical Methods in Fluid Dynamics. Lecture Notes in Physics, Vol. 218, pp 227-280, Springer-Verlag, 1985.

M. Holt and C. Pace, "Calculation of Flow in a Supersonic Compression Corner by the Dorodnitsyn Finite Element Method," 10th Intl. Conf. on Num. Methods in Fluid Dynamics, Beijing, People's Republic of China, June 23-26, 1986. Proceedings. Lecture Notes in Physics, Vol. 264, pp 314-319, Springer-Verlag, 1986.

BAIL IV lecture published in Proceedings, pp 80-88, Boole Press, Dublin, Ireland, 1986.

J.D. Brown, J.L. Brown, M.I. Kussoy, C.C. Horstmann and M. Holt, "Two Component LDV Investigation of 3-Dimensional Shock/Turbulent Boundary Layer Inter-

actions", AIAA 25th Aerospace Sciences Meeting, Reno, NV, January 1987, Paper No. AIAA-87-0553.

E. Ettehadieh and M. Holt, "Effect of Normal Injection of a Turbulent Jet on Boundary Layer Flow in a Pipe", submitted to Computer Methods in Applied Mechanics and Engineering.

M. Holt, Y. Kliafas and W.D. Bachalo, "Measurements of High Speed Turbulent Air Flow in a 90 Bend Using Laser Doppler Velocimetry", AIAA 3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 1985, Paper No. AIAA-85-4066.

V. Daru, "Analysis of Implicit Finite Difference Schemes for the Solution of the Euler Equations", Text of Lecture given at UC Berkeley and NASA Ames Research Center, October, 1985. To be published as a report of Ecole Nationale Supérieure d'Arts et Métiers, Paris, France.

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